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14. ABSTRACT
Our research under this award explored several problems in theoretical and experimental quantum nonlinear optics. We published significant new results on the design of ultra-low energy photonic switches, and on single-atom switching of the phase of a coherent optical signal field. We also conducted theoretical and computational research on bifurcations in single-atom cavity QED, which we hope to complete and submit for publication in the near future.

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Report Title

Functionalizing ultra-low energy nonlinear optics: analysis and suppression of quantum fluctuations

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Our research under this award explored several problems in theoretical and experimental quantum nonlinear optics. We published significant new results on the design of ultra-low energy photonic switches, and on single-atom switching of the phase of a coherent optical signal field. We also conducted theoretical and computational research on bifurcations in single-atom cavity QED, which we hope to complete and submit for publication in the near future.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

H. Mabuchi, "Cavity-QED models of switches for attojoule-scale nanophotonic logic," Phys. Rev. A 80, 045802 (2009).

M. A. Armen, A. E. Miller and H. Mabuchi, "Spontaneous Dressed-State Polarization in the Strong Driving Regime of Cavity QED," Phys. Rev. Lett. 103, 173601 (2009).

Number of Papers published in peer-reviewed journals: 2.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

H. Mabuchi, "Dynamic complexity in nonlinear nanophotonics," 3/3/09 DARPA MTO Symposium.

H. Mabuchi, "Photonic circuits for classical and quantum signal processing," 4/22/09 University of California at Berkeley.

H. Mabuchi, "Future photonics: quantum, nonlinear, nano," 4/28/09 DARPA DSO off-site.

H. Mabuchi, "Nonlinear dynamics and quantum fluctuations in single-atom cavity QED," 5/21/09 KITP Santa Barbara.

H. Mabuchi, "Photonic circuits for classical and quantum signal processing," 7/6/09 University of Bonn.

H. Mabuchi, "From Jaynes-Cummings to Rouse-Zimm: interdisciplinary quantum optics," 10/6/09 Stanford University.

H. Mabuchi, "Photonic circuits for classical and quantum signal processing," 11/9/09 Stanford University.

Number of Presentations: 7.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

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(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Dmitri Pavlichin	0.50
Gopal Sarma	0.50
Anthony Miller	0.17
FTE Equivalent:	**1.17**
Total Number:	**3**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Hideo Mabuchi	0.05	No
FTE Equivalent:	**0.05**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Statement of the problem

Basic and applied research efforts in photonics, quantum optics and nonlinear science have progressed at breakneck pace in recent years, making this an opportune time to reassess the practical frontiers of optical information-processing systems. Several specific advances are particularly significant in this regard:

- Techniques for fabricating integrated (chip-scale) optical waveguides, resonators and circuits are maturing to the point where they may become commercially feasible for large-scale production in the foreseeable future [1].
- Physicists and electronic engineers are beginning to demonstrate that strong-coupling phenomena of cavity quantum electrodynamics (cavity QED), with critical photon numbers of order unity, can be realized in mechanically robust solid-state systems [2].
- Modeling techniques are being developed to analyze the interplay of quantum fluctuations with mean-field nonlinear dynamics in cavity QED systems, providing new insight into the ways that quantum fluctuations destabilize classical switching dynamics and signal amplification at ultralow (atto-Joule) energy scales [3].

Looking five-to-ten years into the future, one can envision a convergence of these three advances that would lead to the realization of ultralow-energy optical switching devices and coherent optical signal-processing devices based on strong coupling phenomena of solid-state cavity QED. Many bifurcation phenomena in neutral-atom cavity QED, which could potentially be functionalized for nonlinear-optical signal processing, are predicted to occur [4] on energy scales of tens to hundreds of near-infrared photons (well below 10^{-15} Joule). In solid-state implementations analogous phenomena should be accessible with very fast (picosecond) timescales [5]. *The primary obstacle to prototyping significant and realistic photonic devices is the inevitable presence at these ultralow energy- and time-scales of substantial quantum fluctuations* [3,4], which we must learn to suppress by understanding optimal tradeoffs among power dissipation, speed and stability, and through the use of design techniques such as optical feedback and coherent coupling within device arrays. The goals of our research have been to utilize single-atom cavity QED systems to further our understanding of the interactions of quantum fluctuations nonlinear phenomena, and to seek realistic device designs in which ultralow-energy optical switching can be achieved in spite of quantum fluctuations.

Summary of results

Two major results were obtained during the performance period and published in refereed journals with acknowledgment of support from this award. The first [6] was a theoretical study of a design for a class of robust ultralow-energy optical switches based on cavity quantum QED with a single multilevel atom (or comparable bound system of charges) coupled simultaneously to several resonant field modes. A limit theorem for quantum stochastic differential equations was used to show that the input-output behavior of such devices corresponds to a simple scattering matrix in a type of strong-coupling limit that seems natural for nanophotonic systems. Numerical integration was used to show that the behavior of detailed physical models for such switches approximates that of the simple scattering matrix in a realistic regime for the physical parameters, and that it is possible in the proposed cavity-QED

configuration for low-power optical signals to switch higher-power signals at attojoule energy scales. In unpublished follow-up work we have shown that such switches can be cascaded to implement universal classical logic gates such as NAND and NOR. Our second important result [7] was an experimental demonstration of the phenomenon of single-atom phase bistability in cavity QED. We utilized high-bandwidth phase-quadrature homodyne measurement of the light transmitted through a Fabry-Perot cavity, driven strongly and on resonance, to detect excess phase noise induced by a single intra-cavity atom. We analyzed the correlation properties and driving-strength dependence of the atom-induced phase noise to establish that its correspondence with the long-predicted phenomenon of single-atom phase bistability, providing a unique quantitative study of cavity quantum electrodynamics in the strong-driving regime in which one atom interacts strongly with a many-photon cavity field to produce novel quantum stochastic behavior.

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[7] M. A. Armen, A. E. Miller and H. Mabuchi, “Spontaneous Dressed-State Polarization in the Strong Driving Regime of Cavity QED,” Phys. Rev. Lett. **103**, 173601 (2009).